Experimental Characterization of Hysteresis in a Revolute Joint for Precision Deployable Structures

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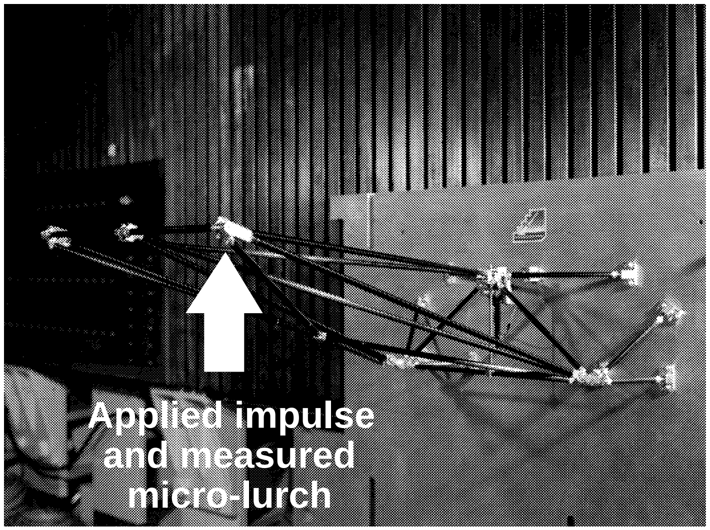
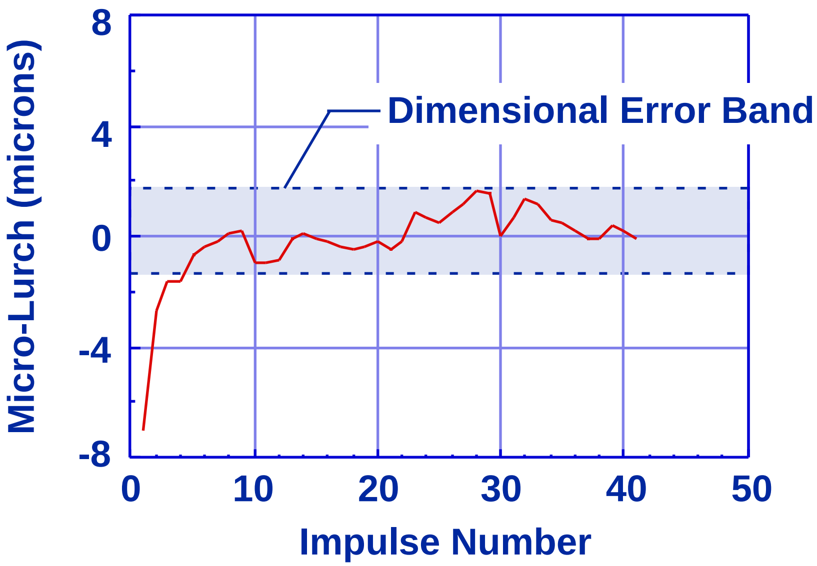
Presentation Outline

- **Summary of past microdynamic test results from precision deployable structures**
- **Discussion of the effects of nonlinear load-cycle response on dimensional stability**
- **Goals of present tests**
- **Present test setup and data reduction procedures**
- **Test results**
- **Development of a deployable primary mirror for a space-based lidar telescope**

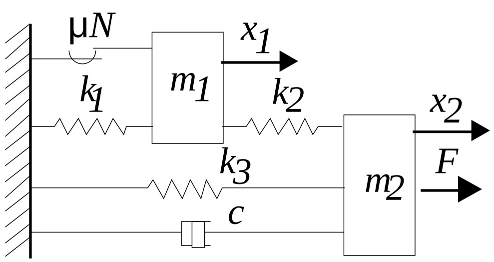
U. of Colorado has Identified Mechanism-Induced Microdynamic Instabilities in a Prototype Deployable Telescope Metering Truss

- **Testing has identified "micro-lurching" which is a dimensional change directly related to friction-induced hysteresis within the joints.**
- **A micro-lurch is a microdynamic INSTABILITY: it occurs ONLY above a certain energy threshold correlated with the hysteresis-collapse loads within the joints.**
- **It currently appears probable that a micro-lurch can be minimized through proper mechanism design, and the next-generation deployable telescope test article is expected to be stable to < .5mm.**

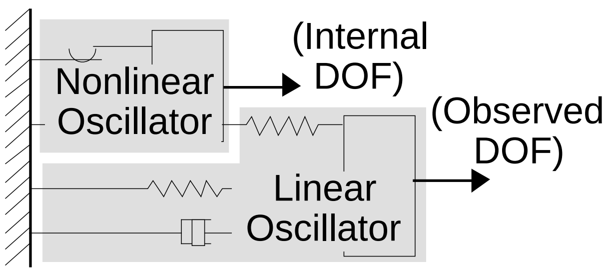




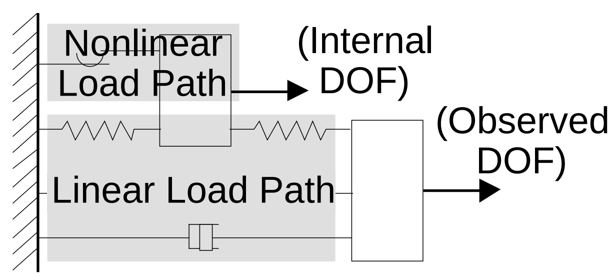
Simplified Load-Transfer Model Illustrates Suspected Relationship Between Friction-Induced Hysteresis and Micro-Lurching



Model Parameters

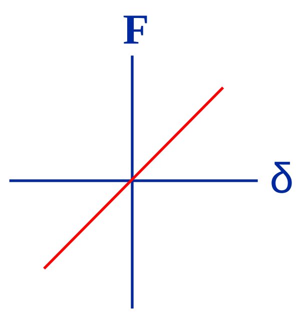


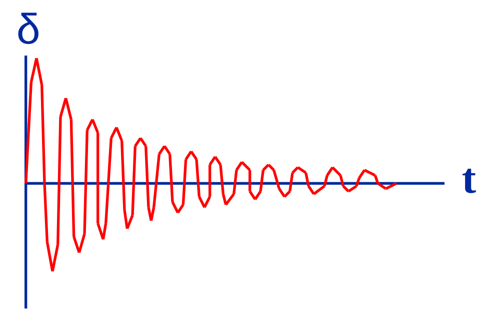
Dynamic-response interpretation



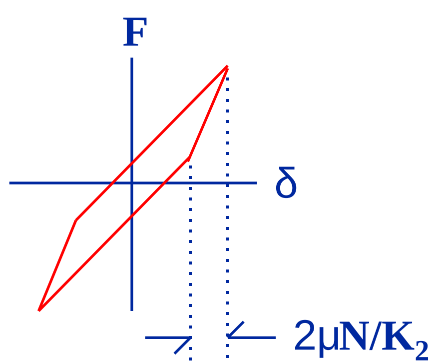
Mechanical-response interpretation

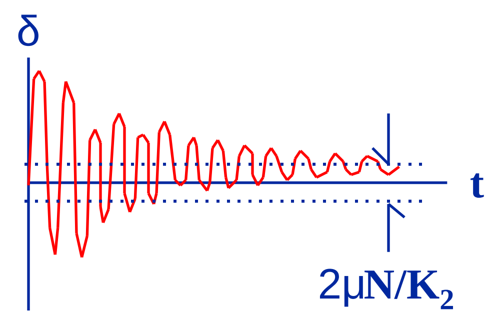
Linear Response Below Stick-Slip Threshold





Nonlinear Response Above Stick-Slip Threshold





Quasi-static hysteresis ⇒ **Micro-lurching equilibrium zone**

Load-Cycle Tests of Precision Revolute Joints

PREVIOUS TESTS:

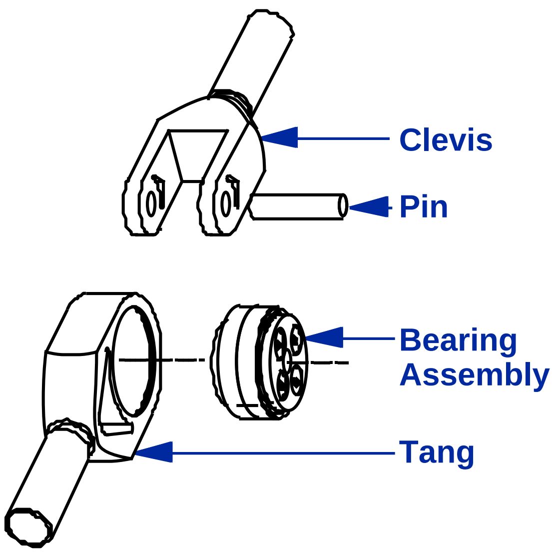
- **Low-load-cycle magnitude response (< 22 N) characterized as LINEAR with no measurable hysteresis.**
- **High-load-cycle magnitude response (> 222 N) characterized as HYSTERETIC with about 1% to 2% loss.**

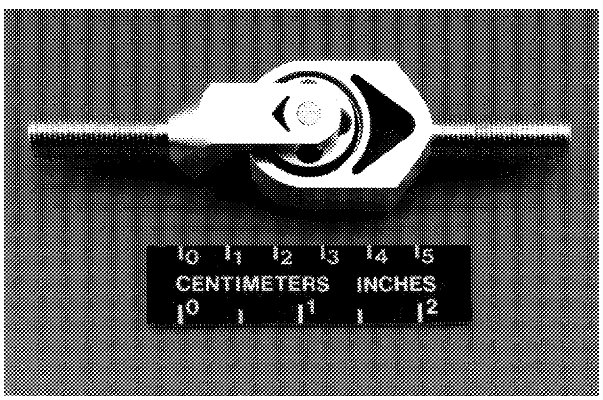
GOALS OF PRESENT TESTS:

- **To quantify the hysteretic response of the precision revolute joints under quasi-static load cycling, and to characterize variations in the hysteretic response due to:**
  - load-cycle magnitude
  - manufacturing tolerances
  - variations in two critical design parameters

Present Test Setup and Data Reduction Procedures

Precision Revolute Joint Test Specimens



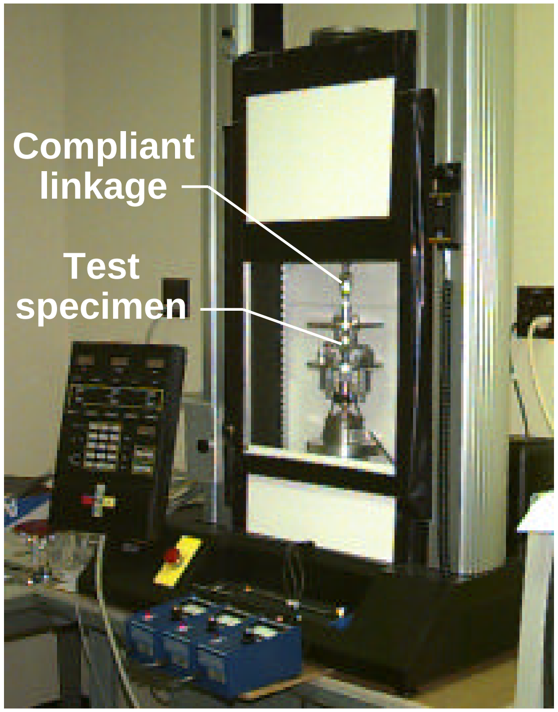


Name	No. tested	Pin fit*	Bearing preload
C-0	1	N/A	N/A
C-a	1	a	N/A
C-b	1	b	N/A
J-a-05	1	a	22-44 N (5-10 lb_f)
J-b-05	1	b	22-44 N (5-10 lb_f)
J-a-10	1	a	44-66 N (10-15 lb_f)
J-b-10	5	b	44-66 N (10-15 lb_f)
J-a-20	1	a	89-111 N (20-25 lb_f)
J-b-20	1	b	89-111 N (20-25 lb_f)

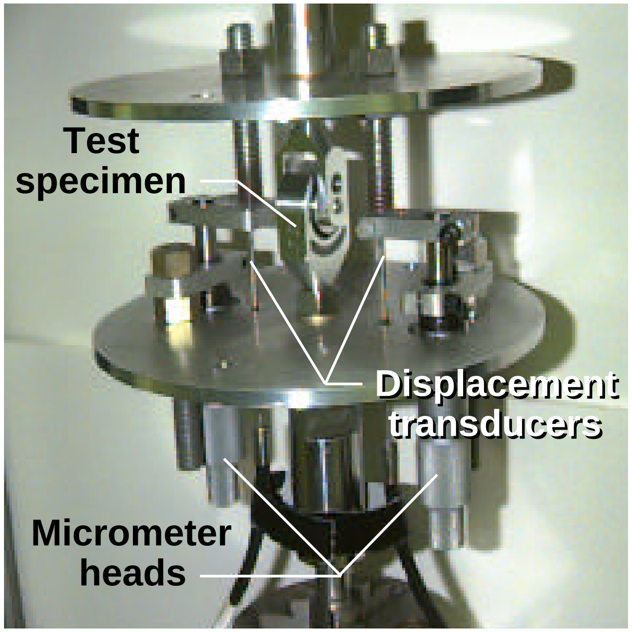
***Difference between pin and hole diameters:**

"a" press-fit 0.069 - 0.089 mm (0.0027 - 0.0035 in)
"b" press-fit 0.043 - 0.064 mm (0.0017 - 0.0025 in)

Test Setup



Load frame with test specimen

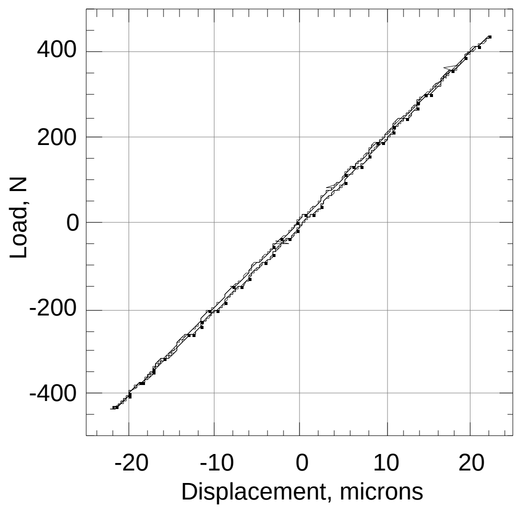


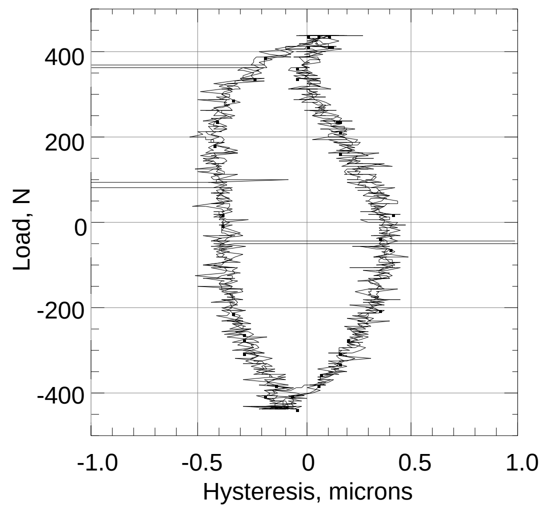
Test specimen and displacement instrumentation

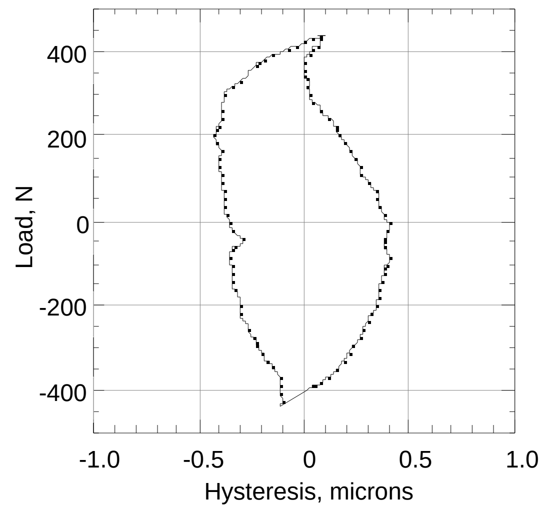
<u>GREAT CARE TAKEN TO MINIMIZE</u>:

- **Instrumentation noise, hysteresis, and nonlinearities**
- **Off-axis loading of specimen**

Data Filtering Algorithms Reduced High-Frequency Noise in Displacement Measurements by an Order of Magnitude







Typical raw response

- Two displacement channels averaged

Typical raw hysteresis

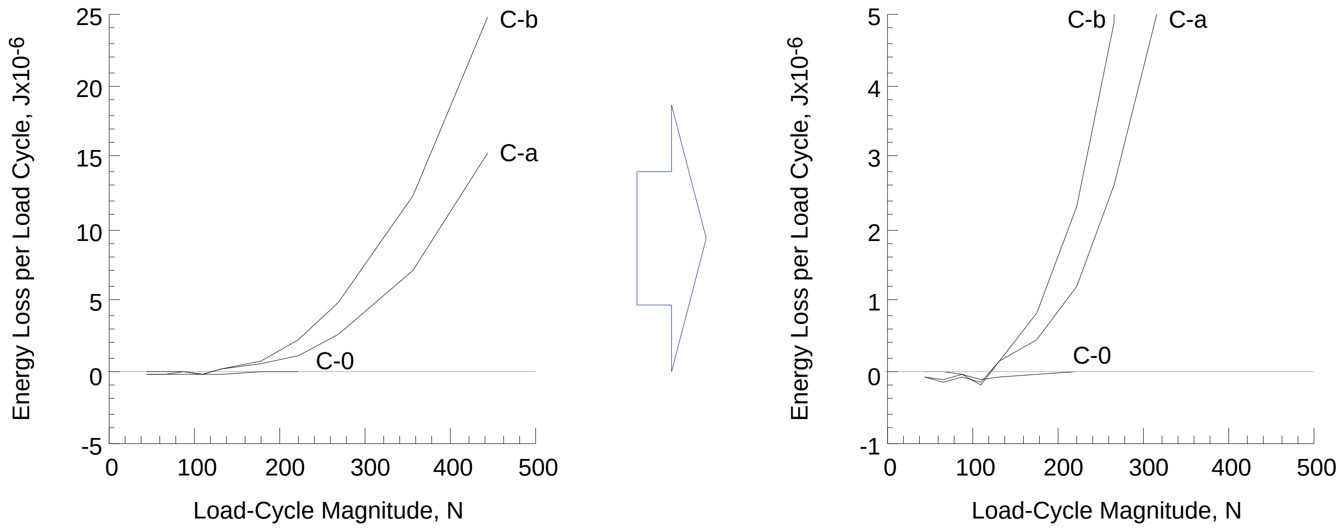
- Best-fit straight line subtracted
- Resolution: O(250 nm)

Typical filtered hysteresis

- Data spikes removed
- High-frequency noise filtered
- Three load cycles averaged
- Resolution: O(25 nm)

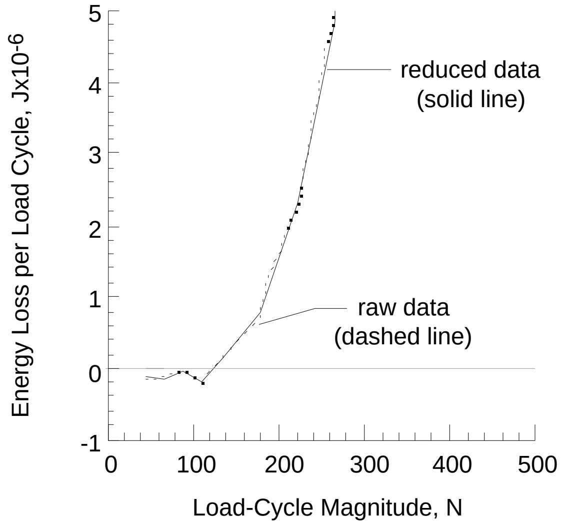
Test Results

MIcro-Slippage in the Press-Fit Pin: Results From the Calibration Specimens

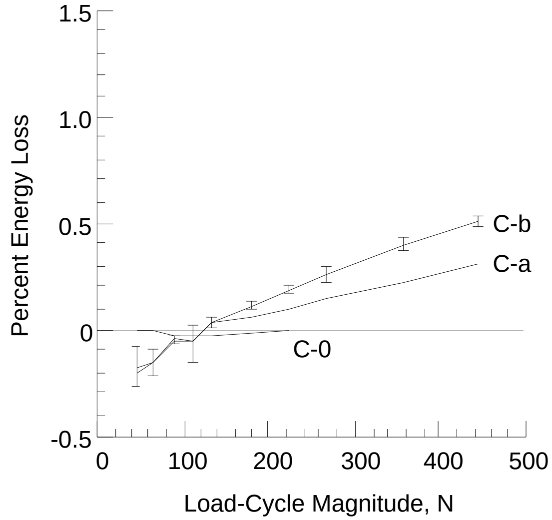


- **Solid aluminum rod (specimen C-0) exhibits no significant hysteretic energy loss.**
- **Both C-a and C-b exhibit no significant energy loss at load-cycle magnitudes below 100 N (22 lb_f).**
- **Both C-b (low-press-fit pin) exhibits approximately 60% to 70% greater energy loss than C-a (high-press-fit pin) at load-cycle magnitudes above 100 N (22 lb_f).**

Bias Error and Random Error in Data



Bias error in energy-loss calculations using raw and reduced data from C-b.

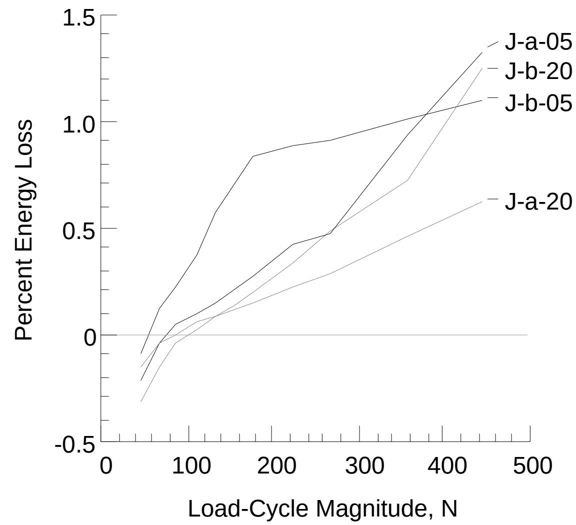


Typical random variability in normalized (i.e., percent) energy-loss calculations

- **Energy-loss calculations are slightly negative at low-load-cycle magnitudes.**
- **Biasing might be due to slight temporal shift of load or displacement data**
- **Numerous sources investigated, but no explanation found**

- **Energy-loss calculations normalized by total elastic strain energy**
- **1(σ) random variability estimated from six tests at each load-cycle magnitude**
- **Small variability at high-load-cycle magnitudes, larger variability at low magnitudes**

Micro-Slippage in the Bearings: Results from the Revolute Joint Specimens

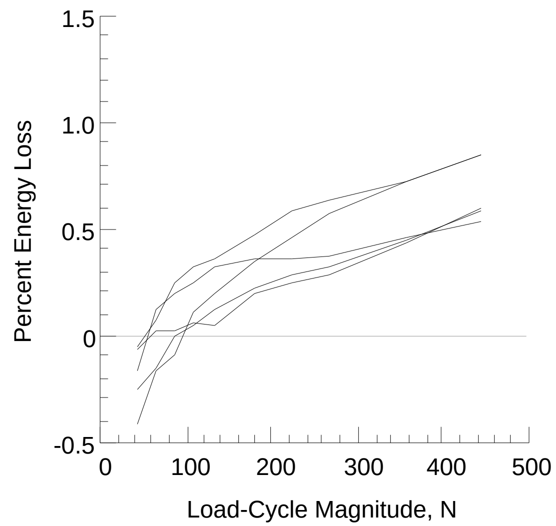


- **Joints exhibit two to three times greater energy loss than calibration specimens with no bearings (C-a and C-b)**

- **Joints with high-press-fit pins (J-a-05 and J-a-20) exhibit less energy loss than joints with low-press-fit pins (J-b-05 and J-b-20)**

- **Joints with high-preload bearings (J-a-20 and J-b-20) exhibit less energy loss than joints with low-preload bearings (J-a-05 and J-b-05)**

Variations in Response Due to Manufacturing Tolerances



- **Five, nominally identical, specimens (J-b-10) exhibited significant variation in response**
- **Bearing manufacturer's specification includes 50% uncertainty in bearing preload (44-66 N) under ideal installation conditions**
- **Machining specification on press-fit-pin includes 50% uncertainty in interference fit (diameter-difference range = 43-64 μm)**
- **Hysteretic energy loss decreases monotonically with load-cycle magnitude and effectively vanishes below 50 N of load-cycle magnitude.**

Summary of Test Results and Implications

- **Significant variability in response was seen due to manufacturing tolerances.**
  - NONLINEAR MICRODYNAMIC RESPONSE IS INHERENTLY PROBABILISTIC.
- **Approximately the same amount of micro-slippage-induced energy loss is exhibited by the angular-contact bearing and the press-fit pin.**
  - ALL INTERFACES ARE IMPORTANT (EVEN “STATIC” ONES)!
- **A weak correlation was seen between preload and the magnitude of hysteretic loss, however preload did not eliminate hysteresis**
  - PRELOADING OF MECHANICAL INTERFACES MIGHT HAVE LITTLE EFFECT ON POST-DEPLOYMENT DIMENSIONAL STABILITY
- **The present data indicate that the response of the joint is EFFECTIVELY elastic for load-cycle magnitudes below approximately 50 N (11 lb_f).**
  - ALTHOUGH NONLINEAR MICRODYNAMIC RESPONSE IS INHERENTLY PROBABILISTIC, IT SHOULD BE INSIGNIFICANT BELOW A CERTAIN STRAIN-ENERGY THRESHOLD.

Development of a Deployable Primary Mirror for a Space-Based Lidar Telescope

or

“A Funny Thing Happened When We Tried to Define the Passive Dimensional Stability Limits of Mechanically Deployed Telescope Structures”

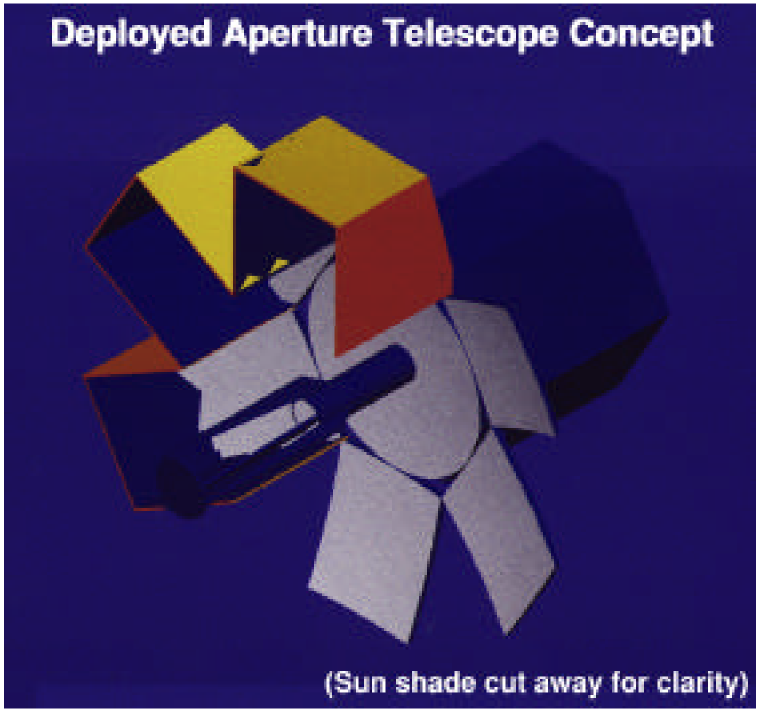
Space-Based Lidar Instrument Types, Science Goals, and Optical Requirements

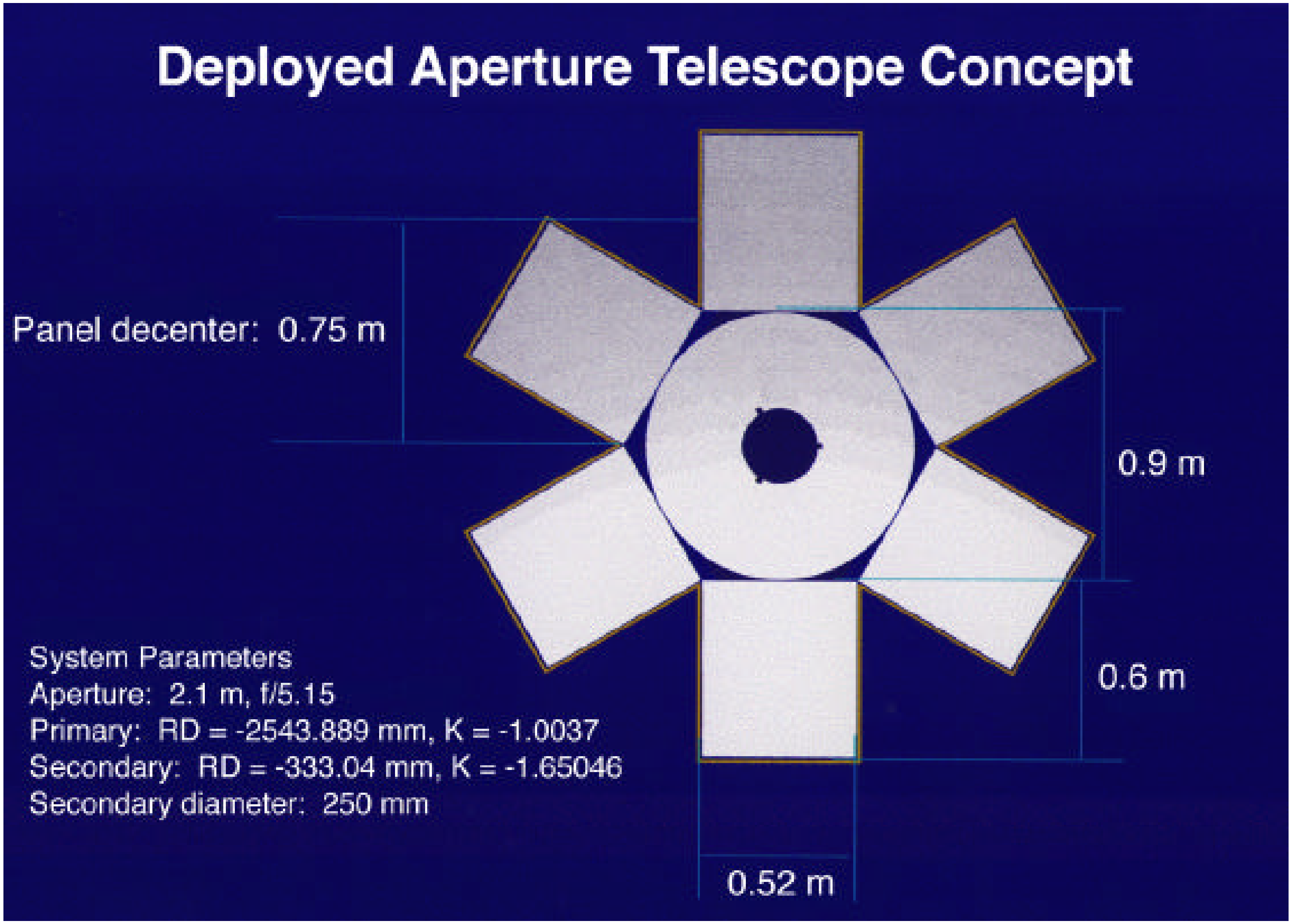
Instrument Type	Science Goal	Optical Requirement
Elastic Backscatter	Clouds and Aerosols	~ 1-5 λ (visible)
Differential Absorbtion (DIAL)	Chemestry	~ 1-5 λ (visible to near UV)
Non-Coherent Doppler Shift	Winds	~ 1-5 λ (visible)
Coherent Doppler Shift	Winds	~ λ/20 (visible)

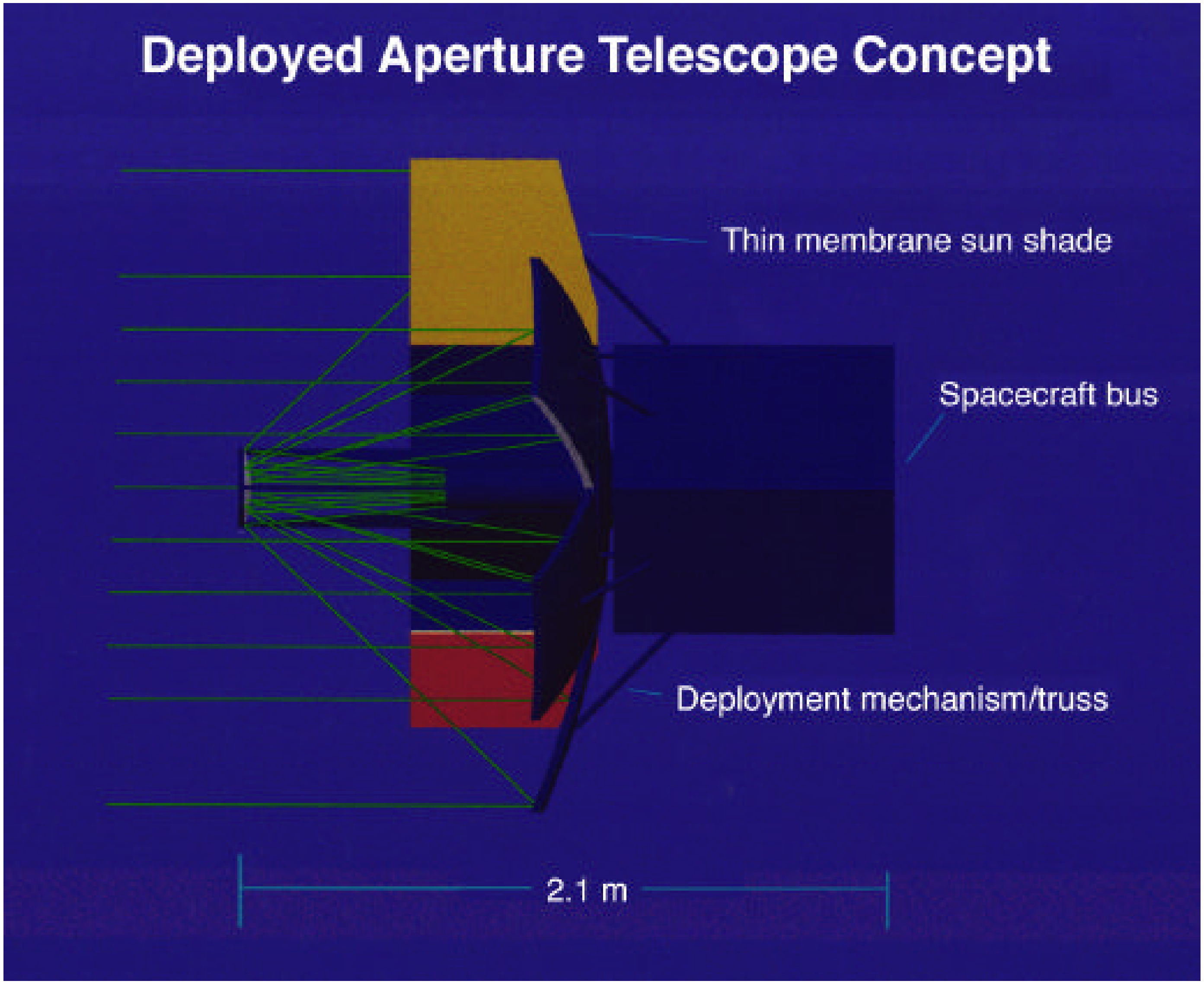
- **Most of the lidar science instruments employ "light-bucket" quality telescopes whose optical figure requirements are substantially less strict than imaging instruments.**
- **Current test experience with high-precision deployment mechanisms indicates that it might be possible to PASSIVELY maintain the necessary optical alignment of a deployable (incoherent) lidar telescope mirror (i.e., ~.5μm microdynamic stability)**

“Low-Risk” Deployable Telescope Concept for NMP Lidar Mission (EO-3 Mission Opportunity)

- Fixed .9-m (state-of-the-practice) primary and fixed secondary.
- Six independently deployable .5 x .6-m primary segments (advanced technology) with independent thin-membrane sun shroud segments.
- “Simple” 1-dof reflector deployment kinematics.
- Factor of four increase in primary reflector area through deployment (deployed area equivalent to 1.8-m aperture).
- CLEAR OPTICAL PATH IN STOWED CONFIGURATION.




Deployed Aperture Telescope Concept
Panel decenter: 0.75 m
0.9 m
0.6 m
0.52 m
System Parameters
Aperture: 2.1 m, f/5.15
Primary: RD = -2543.889 mm, K = -1.0037
Secondary: RD = -333.04 mm, K = -1.65046
Secondary diameter: 250 mm


Deployed Aperture Telescope Concept
Thin membrane sun shade
Spacecraft bus
Deployment mechanism/truss
2.1 m

Summary of Deployable Lidar Telescope Feasibility

- **The optical telescope assembly concept is "sporty" by most standards (i.e., light-weight and fast!)**
- **A 2-m-class deployable telescope is technically feasible by the year 2000.**
- **Instrument mass would be ~50 kg and would package in a Pegasus.**
- **Instrument could probably use current composite mirror technology which gives < 1 μm surface figure with near-zero CTE and an areal density of ~7 kg/m^2.**
- **A 2-m-class deployable telescope primary mirror is planned to be built in 1998 for ground microdynamic testing.**
- **Currently, it is felt that such an instrument could be built to achieve the necessary dimensional stability requirements passively. THIS DEMONSTRATION ESSENTIALLY ESTABLISHES THE THRESHOLD BELOW WHICH ACTIVE ALIGNMENT CONTROL IS NECESSARY.**